AD-A040 649 NATIONAL WEATHER SERVICE STERLING VA TEST AND EVALUA--ETC F/G 4/2

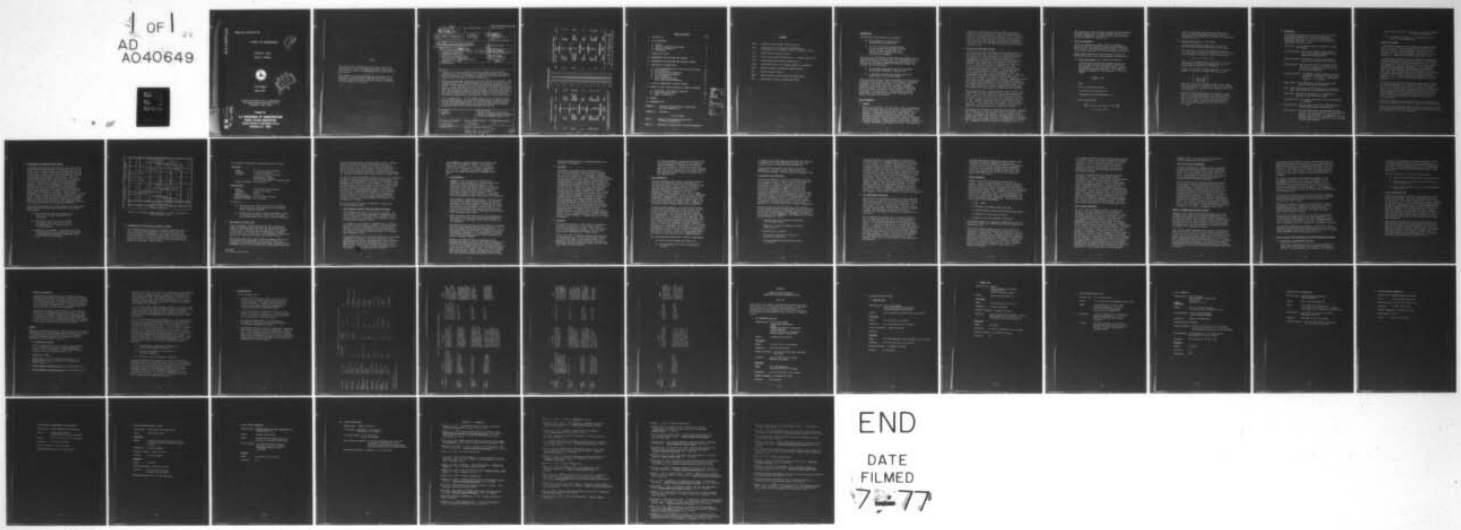
SURVEY OF ANEMOMETERS.(U)

MAR 77 R J STONE, J T BRADLEY DOT-FAA-ER-450-029

UNCLASSIFIED FAA-RD-77-49 NL

1 OF 1

AD
A040649



END

DATE
FILMED
7-77

ADA040649

Report No. FAA-RD-77-49

SURVEY OF ANEMOMETERS

12

NW

Richard J. Stone

James T. Bradley

DDC
JUN 17 1977
C

Final Report

March 1977

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

Technical Report Documentation Page

1. Report No. 18 FAA-RD-77-49 19	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle 6 SURVEY OF ANEMOMETERS. 12 47p.		5. Report Date 11 Mar[redacted]977 6. Performing Organization Code W544
		8. Performing Organization Report No.
7. Author(s) 10 Richard J./Stone [redacted] James T./Bradley		
9. Performing Organization Name and Address Commerce NOAA,/National Weather Service Test & Evaluation ~~Division~~ Lab (W54) 408610 Observation Techniques Development & Test Branch Sterling, Virginia 22170		10. Work Unit No. (TRAIS) 11. ~~Contract or Grant No.~~ 15 DOT-FAA-ER-450-029 new
		13. Type of Report and Period Covered 9 Final Report,
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research & Development Service Washington, D. C. 20590		14. Sponsoring Agency Code ARD-451
15. Supplementary Notes		

16. Abstract

A survey of the field of anemometry was made to assess recent advances in instrumentation. The purpose was to find commercially available wind systems which could replace, on a cost-effective basis, the F420C wind system which is presently used by the FAA for aviation observations.

A search of the pertinent literature for the past ten years was conducted. Over 30 manufacturers of wind sensing equipment were contacted, and discussions were held with research groups who have used the new generation equipment in field studies. It was found that most of the advances have resulted in lower starting speeds and greater instrument bandwidth, since much of the recent meteorological effort has been directed toward micro-meteorological (turbulence) measurements. While the ruggedness, reliability, and range necessary for aviation use have not been primary considerations of manufacturers, there are several commercially available wind systems which could replace the F420C on a cost effective basis.

It is recommended that: (1) for the near future, any one of several suitable cup and vane or propeller on a vane wind systems be used for aviation purposes; (2) the vortex wind sensor mounted on a vane be thoroughly field tested; and (3) that the nonmoving part vortex vector anemometer and hot-film anemometer undergo testing and their continued development be monitored.

17. Key Words Anemometer Wind	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	48	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

408610 4B

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	WIND MEASUREMENT	1
	A. General	1
	B. Sampling and Representativeness	2
	C. Theory of Anemometry	3
	D. Definitions	5
3.	PRESENT WIND SYSTEM	6
4.	REQUIREMENTS FOR CANDIDATE WIND SYSTEMS	7
5.	RECOMMENDED SPECIFICATIONS FOR CANDIDATE SYSTEMS	8
6.	DESCRIPTION OF SENSOR TYPES	9
	A. Cup Anemometer/Propeller & Wind Vane Wind Systems	10
	B. Sonic Anemometer	13
	C. Hot-Wire/Hot-Film Anemometers	14
	D. Ion Displacement Anemometer	15
	E. Vortex Anemometer	16
	F. Laser Doppler Anemometer	17
	G. Laser Scintillation Anemometer	18
7.	SURVEY OF COMMERCIALLY AVAILABLE SENSORS	18
8.	IMPACT OF SOLID STATE TECHNOLOGY ON CURRENT TECHNIQUES	19
	A. Advantages of Solid-State Technology	19
	B. Current Man/Machine Mix	20
	C. Impact of Automation	21
9.	SUMMARY	21
10.	RECOMMENDATIONS	23

APPENDIX I - Operating Specifications of Commercially Available Anemometers

APPENDIX II - References

LIST OF TABLES

TABLE I - Summary of Operational Specifications for Selected Anemometers

TABLE II - Comparison of Commercially Available Anemometers

ACRONYMS

AMOS	Automatic Meteorological Observing System
ESSA	Environmental Science Services Administration (Predecessor of the National Oceanic & Atmospheric Admin.)
FAA	Federal Aviation Administration
FMH #1	Federal Meteorological Handbook No. 1 - Surface Observations
ICAO	International Civil Aviation Organization
LASER	Light Amplification by Stimulated Emission of Radiation
NOAA	National Oceanic & Atmospheric Administration
NWS	National Weather Service
RAMOS	Remote Automatic Meteorological Observing System
ERL	Environmental Research Laboratories, NOAA

1. INTRODUCTION

The objective of this survey is to evaluate:

(1) The performance of new-generation wind measuring equipment; and

(2) The cost of operation and maintenance of this equipment as compared to present National Weather Service (NWS) and Federal Aviation Administration (FAA) wind measuring equipment.

This survey has concentrated on wind measuring equipment that is designed primarily for aviation use. As no standards have been specifically developed for wind speed and wind direction for aviation use, this survey examines existing wind sensors and develops criteria based upon:

(1) the measuring requirements set forth in Federal Meteorological Handbook #1 (FMH #1), and

(2) a comparison with the F420C System which is in general use by the FAA and the NWS.

Also, the report includes a general discussion of the principles of operation of each sensor type, and an evaluation of expected performance under field conditions. In the strict sense, anemometer is the general name fôr instruments designed to measure the speed of the wind. With the advent of nonmoving part wind sensors, the term has been broadened to include the measurement of wind direction. In this survey we use the broad sense of the definition and include instruments that measure both direction and speed.

2. WIND MEASUREMENT

A. General

Wind is air in motion. For this report, wind is considered to be the horizontal motion of the air past a given point. This motion is a vector quantity and must be represented by two numbers: one denoting direction, the other, speed. The direction of the wind is universally accepted to be the direction from which the wind is blowing. Speed is frequently reported in knots or lately meters per second (m/s). Besides direction and speed, a third quantity of the wind is turbulence--irregular and random fluctuations in velocity. The degree of

turbulence is indicated by a quantity known as gustiness. In FMH #1 a gust is defined as a rapid fluctuation in wind speed with a peak greater than or equal to 8.7 m/s (17 knots) and with a variation of 5.1 m/s (10 knots) or more between peaks and lulls. When observed wind speeds are averaged over a one-minute interval, the peak gusts during a strong-wind situation can be 20 to 50% higher than the one-minute average (Atkinson, 1971).

B. Sampling and Representativeness

An instantaneous point measurement is only representative of some atmospheric state (e.g. wind) over a small-time interval and space volume. Many samples must be taken and this data base then used to build an average over some desired representative time period. The desired averaging interval generated either numerically or by a built-in long-time constant in the sensor will vary depending upon sensor use. For air pollution and turbulence measurements, a short averaging interval is needed; for aviation observations, a longer averaging interval is needed. A one-minute average is the current reporting procedure specified in FMH #1. The International Civil Aviation Organization (ICAO, 1967) recommended a two-minute average for airport use. In addition, Beran (1974) shows that a two-minute wind is optimum for predicting the winds a few minutes in advance. Representativeness of the wind includes examination of both speed and direction. Koren (1973) after examination of gust statistics concluded that for aviation purposes the use of a single sensor giving a five-second peak gust in the preceding ten-minute period provides an acceptable stable statistic for indicating wind variability.

The representativeness of wind direction is more complex. Ito (1969) did a year long comparison study at Tokyo International Airport using one wind sensor at the regular observing point and another at point of touch down. For wind speeds of 2.6 m/s (5 knots) or more, 76% of the directional differences were 14° or less. However, differences between wind direction at the two sites exceeded 34° in 1.6% of the sample, usually during a wind shift. He concluded that one anemometer does not give sufficient representativeness at a large, busy airport.

The question as to whether one anemometer can adequately represent wind conditions at an airport is not within the scope of this report. The answer, does, however, color our considerations as to what is considered the important instrument design criteria. Badgley (1970) lists nine theoretical considerations in instrument design before he discusses the practical considerations of field use: ruggedness, reliability, ease of replacement, and cost.

For aviation use, these practical considerations are paramount. The fast starting time, the quick response, and the high frequency measurements, so needed for air pollution studies are not as critical in aviation use.

C. Theory of Anemometry

We will not develop the complete theory of anemometry since this task has already been ably covered by MacCready and Jex, 1964. The following outline, however, will serve to give some background to various terms used in this report.

Meteorological sensors can be divided into two types of systems each with a unique dynamic response characteristic:

(1) First Order System (e.g. Propeller Anemometer):

A nonoscillatory system whose response depends only upon the input and first derivative of the output. The response to a step input monotonically increases towards the new equilibrium value. This system is completely defined by a "time constant" T. For this system

$$\dot{y} + \left(\frac{1}{T}\right) y = f(t)$$

where

f(t) is the forcing function,

y is the sensor indication, and

$\dot{y}$ represents the time derivative of y.

For a step function

$$\left[f(t) = 0 \text{ for } t \leq 0;\ f(t) = A \text{ for } t > 0\right]$$

$$y = A\left(1 - e^{-t/T}\right)$$

where T is the time required for the system to reach 63% of the final equilibrium value (A). Similar equations can be developed for a response to a sinusoidal forcing function.

(2) Second Order System (e.g. Wind Vane):

A system whose response depends on the input and both the first and second derivatives of the output.

The solution of a second order differential equation to a step input is usually characterized by an "overshoot" and an oscillation frequency. For this type system

$$\ddot{y} + 2\zeta\,\omega_n\,\dot{y} + \omega_n^2\,y = f(t)$$

where ζ is the damping ratio for overshoot (e.g. actual vane damping to critical vane damping) and ω_n is the undamped natural frequency of the system.

The percent overshoot (relative magnitude of successive maxima, A_1, A_2) and the damping ratio are related:

$$\zeta = \left[1 + \left(\frac{\pi}{\ell_n A_1/A_2}\right)^2\right]^{-\frac{1}{2}}$$

Reference to step and frequency response curves shows that a damping ratio of between 0.5 and 0.7 is considered desirable--having a reasonably fast response without too much overshoot.

MacCready and Jex (1964) also point out that to match phases up to higher frequencies, the response distance (D_A) of the first order system (cup) should equal the delay distance (D) of the second order system (vane) for all wind speeds. A more complete discussion of the cup and vane anemometer will be given later in this report.

D. Definitions

The following definitions are listed in either the Federal Meteorological Handbook # 1 (1975), the Glossary of Meteorology (Huschke, 1959) and Guide to Meteorological Instruments (WMO, 1971) or agreed to by the majority of manufacturers' specifications.

Anemometer: Any instrument designed to measure the speed of the wind.

Critical Damping: That value of damping which gives the most rapid transient response which is possible without overshoot.

Damped Wavelength: The product of the wind speed and the time for one complete vane oscillation.

Delay Distance: The value defined by $D = T_D V$ where T_D is the time for a vane to move from 0 to 50% of the final equilibrium value, and V is the free stream air wind.

Distance Constant: The passage of wind (in meters, feet, etc) required for the output of a wind sensor to indicate about 63% of a step-function change of the input speed.

Fastest Mile: The fastest speed, in miles per hour, that 1 mile of wind passes the station

Gust: Rapid fluctuations in wind velocity with a variation of 5.1 m/s (10 knots) or more between peaks and lulls.

Light Wind: The wind is considered to be light when the speed is 3.1 m/s (6 knots) or less.

Peak Wind Speed: The highest instantaneous wind speed observed or recorded.

Starting Speed: The air speed at which the sensor performs to within manufacturers' specifications.

Time Constant: The time required for any wind measuring device to detect and indicate about 63% of a step-function change in the input wind. The response of the instrument should be such that about 95% of a step-function change would be indicated in a period equal to three time constants.

Vane Damping Coefficient: The ratio of actual vane damping to critical vane damping.

Wind: As used in this report, the horizontal motion of the air past a given point.

3. PRESENT WIND SYSTEM

The FAA and NWS presently use the F420C wind measuring system. Use of this series began in the mid-1940's. A system of this series consists of a cup-driven magneto coupled to a meter calibrated in knots, and a spread-tail vane coupled to an indicator by a d.c. syncro-transmitter (Weather Bureau, 1970; Standards for Weather Bureau Field Programs (SWBFP, 1967).

The instrument is rugged and has been designed for dependable, continuous operation. The sensor is capable of measuring winds to 103 m/s (200 knots) and can withstand exposure to a 72 m/s (140 knots) wind for a period of five minutes without damage to the equipment or change in calibration. It is, therefore, capable of measuring peak hurricane winds as recommended in SWBFP, and should withstand the expected extreme winds and peak gusts. Gusts as high as 66 m/s (130 knots) can be expected at coastal Florida airport locations once every 100 years (Atkinson, 1971). Inland values will be somewhat lower (see Sissenwine et al., 1973 for additional information on expected peak gusts).

The reported values of wind speed under steady-state conditions are nominally accurate to ± .51 m/s (± 1 knot) for wind speeds to 51 m/s (100 knots), and ± 1.0 m/s (± 2 knots) for speeds from 51 m/s to 103 m/s (100 - 200 knots); however, the variability under field conditions and the dynamic response characteristics of cup anemometers (to be discussed later) reduce the accuracy under extremely gusty conditions to something on the order of ± 10% of the true value within the range of 0 to 51 m/s (0 to 100 knots).

One major disadvantage of the system is that the outputs are not as easily automated as the output of a number of the newer sensors.

While no time (distance) constants have been specified for the F420C wind tunnel tests by Crouser, 1967, indicate a mean-distance constant of 8 meters (26.2 feet) for the system.

4. REQUIREMENTS FOR CANDIDATE WIND SYSTEMS

A candidate wind system is one which will meet aviation wind needs while assuring continuity of historical data. At the present time, no standards have been developed expressly for aviation use. In FMH #1 observation techniques are the same for both aviation and synoptic use with differences lying in codes, timing, and frequency of observation. Since our candidate wind system serves the dual purpose of collecting data for both synoptic and aviation use, the continuity of record is necessary for statistical and climatological purposes. Accurate wind measurements above, say 51 m/s (100 knots), might not be significant for operational aviation use, but are necessary for extreme wind analysis; and thus, the requirements are modeled on the existing wind sensor (F420C) presently in operation. Figure 1 (after Mazzarella, 1972) indicates the ranges of application of a number of sensor types, along with some typical constants for these ranges. For our survey, the range of interest is the synoptic scale, and added to the inventory of sensor types listed by Mazzarella, we will also discuss the vortex shedding, mounted on a vane and nonmoving-part vortex shedding anemometers.

Aside from having operational characteristics which allow their classification as synoptic-scale instruments, the candidate system should:

(1) Operate over the same speed range as the sensor which is under consideration for replacement.

(2) Have digital output for ease of remoting. The digital output should allow for the reconstruction of the "fastest mile" as required by FMH #1.

(3) Have ease of maintenance. Since there could be a large-scale use of these instruments, the training of technicians and frequency of maintenance and repair becomes a consideration.

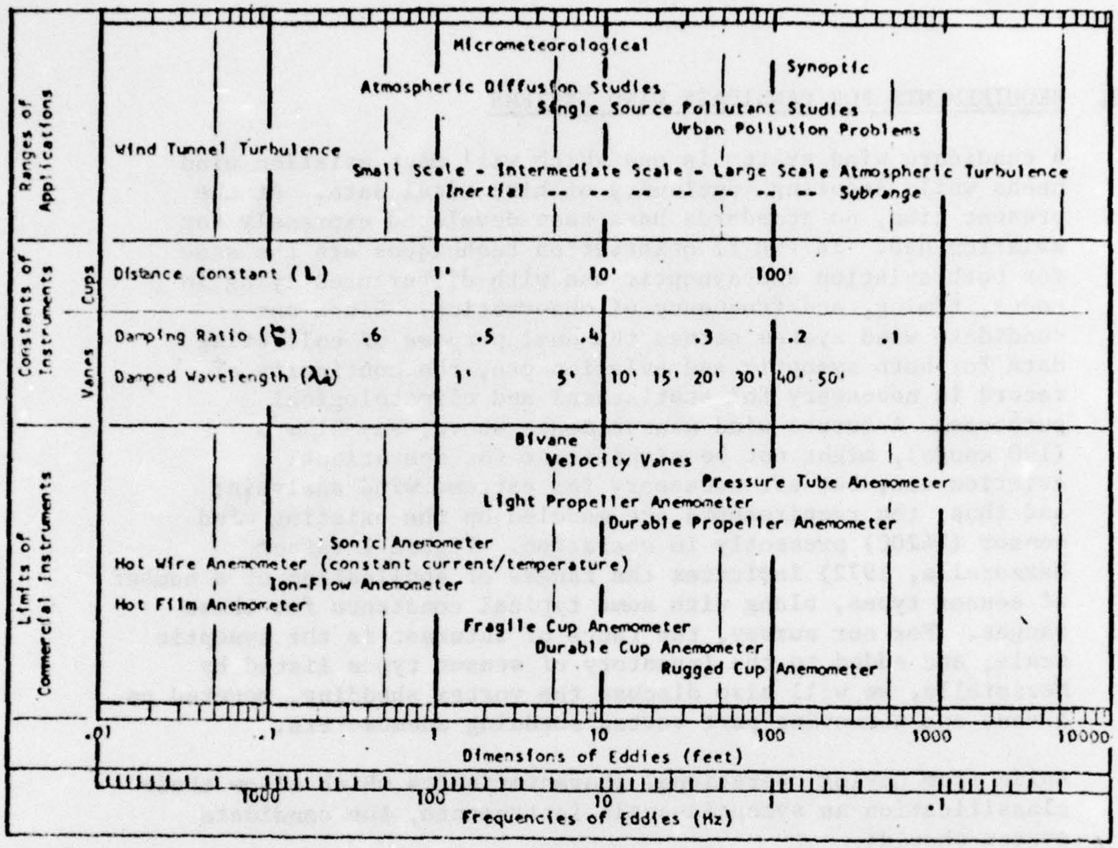


FIGURE 1. Approximate Ranges, Constants, & Limits of Wind Sensors (From Mazzarella, 1972)

5. RECOMMENDED SPECIFICATIONS FOR CANDIDATE SYSTEMS

The recommended specifications for a candidate system were based partly upon the F420C's operational characteristics since that system meets FMH #1 requirements. Also used as input were the criteria developed by the Weather Bureau (ESSA, 1969) for synoptic observing systems. Finally, we determined that the extremely low sensor starting speeds required for air pollution studies are not needed for operational aviation needs.

The recommended functional characteristics are as follows:

Wind Speed

Range:	0 to 65 m/s (0 to 125 knots)
Threshold:	1.3 m/s (2.5 knots)
Accuracy:	0 to 51.5 m/s (0 to 100 knots):
	$\pm$ .51 m/s (1 knot)or
	5% whichever is greater
	51.5 to 65 m/s (100 to 125 knots): $\pm$10%
Distance Constant:	20 m (66 feet)

Wind Direction

Range:	0 to 65 m/s (0 to 125 knots)
Threshold:	1.3 m/s (2.5 knots)
Accuracy:	$\pm$ 10°
*Damping Ratio:	0.2 to 0.3
*Damped Wavelength:	6 to 12 m (20 to 40 feet)
**Distance Constant:	20 m (66 feet)

In addition,

(1) The signal output should lend itself to automation with the specific type dependent on the anticipated signal processing equipment.

(2) Thought should be given to power requirements, effects of icing, and the effects of exposure to: (a) salt spray along coastal areas, and (b) aircraft emmissions.

6. DESCRIPTION OF SENSOR TYPES

Miyake and Badgley (1967) and Mazzarella (1972) summarized a number of instrument types based upon the physical principle underlying their operation, and that approach will be followed in this report. As will be seen, the new sensors developed over the past ten to fifteen years take advantage of technological advances in solid-state electronics and optical sources.

Wind sensors which rely on the transfer of momentum from the air to the sensor, and illustrated by the pressure plate, cup anemometer, and propeller are the oldest types. Leonardo DaVinci developed the idea for the pressure plate anemometer and the first

*If vane.
**If system is not a vane.

operational model was built by Robert Hooke in 1667. Another group of instruments utilizes the pressure exerted on a stationary sensor and includes pitot tubes, drag spheres, and as a special case, the bivane which seeks a null point of pressure forces acting on the sensor. The measurement of heat-transfer from heated wires is an old method of determining the turbulent structure in wind tunnels (Miyake & Badgley, 1967).

The principle has been applied to sensors used in field experiments leading to a series of hot-wire and hot-film anemometers. The principle of the measurement of the speed of sound waves in the atmosphere is utilized by the sonic anemometer. Another group of sensors uses a laser as an optical light source with the wind speeds determined by either doppler shifts in frequency or by the speed with which scintillation patterns move across a receiver array. The well-known principle of vortex shedding is utilized by another group of sensors with the number of vortices, which are a function of wind speed, measured by acoustic methods. The ion displacement anemometer relates the drift of a stream of ions, produced by the sensor to the wind speed and direction.

The following list describes the operation of commercially available anemometer types.

A. Cup Anemometer/Propeller and Wind Vane Wind Systems

Cup anemometers have been in use for over 125 years. As early as 1850 T.R. Robinson published a fundamental paper in the transactions of the Royal Irish Academy in which he discussed results on experiments with rotating cups used as wind sensors (Hinzpeter, 1975).

Cup anemometers and propellers represent rotating systems each with a specific moment of inertia. The translational energy of the air is transformed into rotational energy with the revolutions per unit times the analog measure of the quantity of air which passed the sensor, i.e. the wind speed (Hinzpeter, 1975).

As discussed earlier, the equation of motion for all rotating anemometers is the same. It involves the inertia, the bearing friction, and the aerodynamic forces due to relative speed between the wind and rotating parts. There are no damping terms, therefore, the response is that of a first-order system with the final rotational rate proportional to the applied wind speed (MacCready and Jex 1964).

A cup anemometer is used to measure the horizontal wind speed, while an independent sensor (a wind vane) is utilized for direction. In the case of a propeller system, either the propeller is mounted directly on a vane, or 2 or 3 propellers are mounted orthogonally, such that each propeller measures one component of the wind.

(1) Cup Anemometer

Wyngaard et al., 1971 points out that the cup anemometer, while thought of as a mundane instrument, has a very interesting dynamic behavior. The difference in drag coefficient between the front and rear faces of the cup, which allows the cup wheel to rotate in a wind, also causes faster response to wind-speed increases than to decreases. This causes wind speed readings in gusty winds to be biased high, and the phenomenon has come to be known as "overspeeding."

The problem was investigated as early as 1929 by Schrenk who developed a simple nonlinear model of cup anemometer response to fluctuating horizontal winds and that these were later shown to be roughly in accord with wind tunnel observations. The discussion of errors inherent in the use of cup anemometers still comes up in the literature (Wyngaard et al., 1971; also see MacCready 1966; Bernstein, 1967; and Ramachandran, 1969).

Izumi and Barad, 1970, estimated that the overspeeding is approximately 10% based upon comparisons with mean wind speeds from sonic anemometers in the lower 30 meters of the atmosphere.

Considerable effort has gone into the design of instruments that have rapid response, small moment of inertia, etc. In order to minimize the known errors, Wyngaard et al., 1971, introduced a method which allows for computer simulation of the nonlinear performance of cup anemometers in turbulent winds thereby providing a means of rapidly assessing the effects of geometry changes.

Recently, the ease with which an instrument can be automated has become a concern. The older cup anemometers, including the F420C which the NWS and FAA has in general field use, use a magneto which develops voltage proportional to the cup wheel's rotational speed. This analog voltage signal does not lend itself to automation, nor to remoting over long distances. Sensors have been developed which use reed switches (Fritschen and Hinshaw, 1972) and light

choppers to develop pulses or frequencies which are a function of wind speed.

(2) Wind Vane

The motion of the wind vane can be described by a second order differential equation with the response to a step input defined by two parameters: Natural frequency and damping ratio. Vane design considerations such as vane blade size and shape, double fin configurations, the substitution of a front fin for a counterweight and optimum damping for various applications have been well documented, (e.g. MacCready and Jex, 1964, Wieringa, 1967, and Wieringa and vanLindert, 1971). Where the desired accuracy is only to $\pm 10^{\circ}$, vane design characteristics play a minor role. There are problems in defining starting speed and distance constant for a vane, because starting speed is a function of the angle of attack of the wind, and the response of the vane to the wind is a damped sinusoidal motion. Therefore, as Mazzarella (1972) points out, the distance constant has been variously defined as the length of wind equivalent to one complete oscillation, the product of the tunnel speed and the time for the vane to describe one damped cycle, and as a point on the envelope of the described oscillation which prepresents 63% of the final equilibrium value. A number of other concepts such as "delay distance" and"decay distance" have been suggested. However, in the recommendations for a candidate system, we have used the constants: "damping ratio," and "damped wavelength."

(3) Propeller

The propeller rotates at a speed which is determined by the pitch of the blades, and the rotation speed is directly proportional to the wind. Also, the propeller has a nearly cosinusoidal response to the wind which leads to two configurations for these sensors.

In the first type, the dynamics of which were discussed by MacCready and Jex, 1964, has the propeller mounted on a vane which keeps it facing into the wind. The response of the vane, already discussed, indicates that this sensor would not be useful in light, variable winds (under about 1.3 m/s (2 knots)).

The second arrangement, discussed by Drinkrow, 1972, is a two-propeller anemometer with the propellers mounted orthogonally. However, as the response curve is not perfectly cosinusoidal, there is an error when the wind is off the axis of the propellers. This error can be significant, i.e. greater than 10% when the wind direction is along the center line of the anemometer pair.

B. Sonic Anemometer

The sonic anemometer uses acoustic techniques to measure wind velocity components, and are either doppler or transit-time devices. Since it has no moving parts which must come into dynamic equilibrium with the flow, it responds rapidly to fluctuations in velocity and is ideally an instrument to study the structure of atmospheric turbulence (Kaimal et al., 1971). Doppler devices depend on backscattering from turbulent temperature and pressure discontinuities. While the concept is well established, performance of these devices has been poor due to low scattering, coefficients, signal dropout, and poor signal-to-noise ratio, (EG&G, 1975). Transit-time devices are either continuous-wave or pulsed systems.

As sound travels through air, its velocity with respect to the ground is the vector sum of the velocity of sound in still air, plus the velocity of the wind; and the velocity of sound in still air is basically functional of air temperature. The continuous wave units make use of a phase shift in a transmitted source frequency. This phase shift along with an accurately measured temperature and the known receiver-transmitter array geometry can be used to calculate the orthogonal horizontal components of the wind. The pulsed units have transducers which are used alternately as a transmitter and receiver, i.e., the sound is propagated in both directions between the transducers in each axis of the array. By use of pairs of measurements, the velocity of sound in still air is eliminated, leaving the velocity of the wind as the only unknown parameter.

The continuous-wave systems have a number of shortcomings:

(1) errors due to spurious sound paths, and

(2) the requirement for continuous application of power.

In addition, the pulsed types are inherently less sensitive to thermal drift in the transducers and these are less subject to drift in their zero-wind calibrations.

More detailed discussions of the theory of the sonic anemometer can be found in EG&G, 1975; Kaimal, et al., 1971; Suomi & Businger, 1959; and Kaimal and Businger, 1963.

C. Hot-Wire/Hot-Film Anemometers

As previously mentioned, the hot-wire anemometer has been used for many years as a research tool in wind tunnels and fluid dynamics. Merceret, 1976, points out that the literature on the subject is extensive and that the foundations are carefully presented by Corrsin, 1963, Hinze, 1959, and Kovasznay, 1965. As more interest developed in determining the details of flow and the structure of atmospheric turbulence, hot-wire and hot-film anemometers began to be used in atmospheric research. The turbulence dissipation spectrum of the atmosphere usually peaks at a wavelength of about 1 mm (Sheih, 1972), and this requires a sensing device which has a fast frequency response and final spatial resolution. The hot-wire anemometer is a suitable choice for this type of measurement.

Hot-wire and hot-film sensors make use of the principle of heat transfer between a heated element and the environment. The type which has gained in acceptance during the past few years is the constant-temperature anemometer (as opposed to the constant-current anemometer). The reasons are as follows (Thermo-Systems Inc., 1975):

* Constant temperature systems are compatible with film-type sensors.

* Operation at constant temperature prevents sensor burn-out.

* Linearization is possible.

* The constant-temperature system can be temperature compensated.

* Constant-temperature systems give a direct d.c. output.

The detecting element of the anemometer is heated by an electric current to a temperature which is typically 225° to 275°C (approx. 437 to 532°F) above ambient. The element is cooled by the wind causing a temperature drop and a resulting decrease in electrical resistance of the element. It should be noted that there is also a term in the heat transfer to still air. With the constant temperature system, the electrical resistance of the element is kept as constant as possible, with temperature changes compensated for by an electronic feedback circuit (Sheih, 1972; SethuRaman and Brown, 1976). While theoretical evaluations based upon heat transfer are available, direct calibration of each element is commonly adopted as this eliminates differences in sensor material, supports, and other unknown factors. Hot films are gaining in use for atmospheric research because they are less susceptible to breakage or fouling, are easier to clean, have a better frequency response than a wire of the same diameter, and give more flexibility of sensor configuration.

D. Ion Displacement Anemometer

The ion deflection anemometer consists of corona electrodes which produce a stream of ionized molecules, which are then collected downstream from their point of injection. If the time the ions spend in the airstream is known and if the ions acquire a velocity component equal to the air velocity (through momentum and/or charge transfer), the air velocity is simply the displacement divided by transit time. Waletzko, 1975, describes the theoretical considerations in some detail.

In the commercially available unit, a corona discharge is used to produce positive ions which are then injected into the wind. The air whose velocity is to be measured is made to flow through the gap between the corona anode and cathode in a direction perpendicular to the electric field. Since it is ambient air which is being ionized, the molecular mass of the ions will be the same as the molecular mass of the moving air stream, and the ions will acquire a velocity component parallel to the air velocity due to both momentum and charge transfer. Further, they acquire this velocity in a time period which is short compared to the time required for the ions to cross the gap (1 nanosecond versus 1 millisecond).

The instrument has no moving parts, and by virtue of its principle of operation measures the wind velocity independent of ambient temperature, pressure and humidity. It does, however, act as an electrostatic precipitator, therefore, the collecting electrode collects particles which must be periodically washed off with water. Also, present configurations do not measure wind velocities above 45 m/s (87.4 knots).

E. Vortex Anemometer

When air flows past an obstruction, a turbulence is created. Above a certain minimum velocity this turbulence assumes a regular pattern of vortices. Vortex anemometers make use of this fact, and the following discussion of the theory behind and principles of operation of vortex anemometers is derived from Colton, 1974. As stated above, when there is relative motion between a body and the surrounding fluid, vortices are formed in the wake. The spacing between these vortices is a well-defined content and is approximately 2½ times the diameter of the obstruction. The vortex frequency (F) is given by the relationship:

$F = S\frac{V}{d}$ Where:

F = Frequency of shedding vortex pairs (Hz)

S = Proportionality constant (now called Strouhal number)

d = Diameter of vortex generator (feet)

V = Speed of fluid flow upstream of generator

The Strouhal number is a function of body size and its shape, which in the case of the commercially available sensors is a cylindrical strut.

The constant Strouhal number has led to many schemes for sensing the vortex stream passage and subsequent use of the technique as a speed sensor. Ideas have included a hot-wire anemometer in the wake, heated thermal resistance elements on the rod, strain gauges and electrical/mechanical transducers. These sensors were successful to one degree or another, but most have not found their way into a practical instrument because of such sensing limitations as: limited bandwidth, fragile construction, low signal-to-noise ratio, and mechanical resonances.

A new sensing technique has been developed which utilizes an ultrasonic beam. An ultrasonic transmitting element transmits a confined beam across the wake of a vortex generating rod to an identical receiving transducer. Passage of a pair of vortices causes one cycle of amplitude modulation on the carrier. The amplitude modulation is due to the beam-scattering effect of the rotating vortices.

Two types of sensors have been developed using this technique. The first is a speed sensor which is incorporated in a vane, and as such has the same response characteristics as those discussed with respect to propellers on vanes. A second series of sensors makes use of the angular properties of an open tube, and is truly a no-moving part sensor. An open tube with a sensor inside will yield a curve which is approximately cosinusoidal as it is rotated from 0^{o} to 90^{o} with respect to the flow. Sensors using six small tubes placed at 60^{o} angles to measure the horizontal wind have been produced. Some of the advantages of these anemometers are their simplicity of design and electronic processing, and the fact that they have been designed to be left unattended for a period of at least one year; however, there has been no field experience with the no-moving part sensor.

F. Laser Doppler Anemometer

The laser doppler anemometer remains a research tool because of its cost, complexity, and the extensive peripheral equipment necessary for its operation. Also, its primary use would be to measure wind shear, (not to replace the anemometer) however, a brief discussion of one commercially available system is included for completeness. The system is the Lockheed Laser Remote Atmospheric Monitoring System which makes use of doppler shifts caused by backscattering from atmospheric particulates. It is a single beam system which emits radiation of 10.6μm. The beam is expanded through a telescope, after a small portion of the energy is reflected by a beamsplitter to be used as a reference, and is transmitted to and focused in the region of interest. Moving atmospheric particulates scatter some of the energy which is collected and collimated by the telescope. A portion of this energy is directed into the detector where it photomixes with the reference beam. The difference in frequency between the local oscillator radiation and the doppler-shifted backscattered radiation is displayed on a spectrum analyzer as a frequency which is proportional to the detected wind velocity component

(Lockheed, 1974). For more details on the various doppler techniques see Schwiesow, 1972.

G. Laser Scintillation Anemometer

The laser scintillation anemometer obtains a spatially averaged wind speed (one component) over ranges from 300 meters to 10 kilometers with a small (4 mW) He-Ne laser. While this method of observation would not allow for continuity of historical data, it is included in this study because it is a possible method of obtaining runway crosswind measurements.

This technique uses the drifting scintillation pattern which arises from wind-transported refractive index irregularities. Drifting scintillation is the cause of the twinkling, or scintillation, of starlight. As different portions of the path contribute to the total scintillation pattern, that pattern is continuously evolving because of the relative speeds of the different sized features it contains. To measure the average component, the receiver uses two apertures spaced along the direction of movement of the pattern. The mathematics required to interpret the signal is presented by Lawrence et al., 1972, the group that first successfully constructed and tested such a system. Atmospheric studies using this technique are discussed by Kjelaas and Ochs, 1974.

7. SURVEY OF COMMERCIALLY AVAILABLE SENSORS

Appendix I lists typical operating specifications for each instrument type, along with at least one manufacturer. The information is derived from the manufacturers' literature on the indicated models. While Appendix I shows the manufacturers' specifications, we have also contacted various users of these instruments to solicit their feelings on the actual operation of various models. For quick reference, the salient features of Appendix I are summarized in Table I.

Table II lists sensor types which are currently available from commercial sources, along with the advantages and limitations of each type and typical price ranges. The information is from Kaimal, 1975, and by personal communication (1976) with Mr. R.M. Brown, Brookhaven National Laboratory, Messrs, C. Ray Dickson, and E. White, NWS Air Resources Laboratory, and Dr. J. C. Kaimal, ERL, Wave Propagation Laboratory. We also have had extensive communications with the various manufacturers and with members of the NWS Test and Evaluation Division and Equipment Development Laboratory.

Our purpose was to determine: how well these sensors stood up under field conditions; how well they matched the manufacturers' specifications; what type of maintenance was needed; were they suited for aviation use, or whether they were just a laboratory instrument. Cost and ability to automate and remote were also of prime concern. And, finally, could a journeyman electronic technician be reasonably expected to install and maintain the equipment.

The results of the survey were rather discouraging. There is tremendous movement in the field of anemometry but the developments have been tied to increased interest in the determination of the micro-scale structure of the wind field. In order to accomplish this, much of the effort has been to lower the starting speed of the instruments. The ruggedness, reliability and range we desire are not the primary consideration of the manufacturers.

The ability to automate and remote is built into the nonmoving part sensors by virtue of their sampling techniques. Two-axis sensors require microprocessing to develop wind speed and direction from sensor output.

Training requirements for most of the new generation sensors are minimal. The sonic anemometer, hot wire, ion, and vortex shedding anemometers are essentially "black boxes" with standard plug-in printed circuits. The laser type, however, does require extensive training.

Sensor care is critical. Table II lists some of the problems encountered with these sensors under field conditions. Of all the nonmoving parts sensors, the vortex shedding anemometer (J-Tec) seems most adaptable to field use. It requires very little maintenance and can be serviced by a journeyman technician.

Like the other nonmoving part sensors, it does require a microprocessor to generate wind speed and direction. It has not been tested extensively under field conditions but there are no inherent design limitations that would preclude field use.

8. IMPACT OF SOLID STATE TECHNOLOGY ON CURRENT MEASURING TECHNIQUES

A. Advantages of Solid-State Technology

Solid-state technology has given us new instrumentation for sensor types, data handling, and presentation of output to the user. We have nonmoving parts sensors. The Instrument

Division of the (Canadian) Atmospheric Environment Service is developing digital readout of wind information for Air Traffic Control Centers (Koren, 1973) and microprocessors have taken over data handling. Recently, an international conference was devoted to automated meteorological systems (WMO, 1975).

The main advantages of solid-state technology are:

(1) sensors have fewer moving parts and are more rugged;

(2) microprocessors can take care of any nonlinearity in calibration; and

(3) increased measurements at less cost per measurement (Pike, 1974).

B. Current Man/Machine Mix

Present wind systems depend upon a man/machine mix and have resultant limitations. The bias by the human observer in wind direction is well known (Lea and Helvey, 1971). Since the changeover from a 16-point compass to the 36-point compass in 1964, the calculation of a wind rose has included various statistical corrections for bias. A further changeover to a digital readout will also need correction for bias since the subjective observer will no longer have input. There is still some observer bias even with the 36-point compass. A digital readout will eliminate this residual bias. However, wind roses will still need correction for bias until that time when all the data used in their construction are from digital readouts.

The problems of the detection and reporting of gusts have also not been resolved. At stations where direct-reading wind dials are used, FMH #1 specifies that they should be monitored as often as possible consistent with other duties. FMH #1 also states that a gust is the maximum instantaneous wind speed observed. Over a period of several years, a continuously measuring automated system will record higher wind gusts (peak winds) than the human observer.

C. Impact of Automation

The F420C has been specified only for steady-state flow. Repetitive measurements at frequent intervals, as performed by automation, will give fluctuations which must be averaged over some sampling time. This new averaging may or may not change published average wind speeds. New gust climatology will be developed. Elimination of the human observer will take directional bias out of wind direction.

Solid-state technology, both of sensor and data handling could affect the continuity of historical data. It should be noted that automation schemes must be thoroughly tested to eliminate the chance of induced bias as has been seen in automated wind direction measurements around the direction north. Since north can be either 0° or 360° this represents a discontinuity which could be averaged as south.

9. SUMMARY

Based upon a literature search and review of commercially available anemometer systems, the anemometer types which meet the criteria for candidate wind systems, without the need for extensive peripheral equipment and which can be expected to operate unattended for long periods of time are:

A. Cup Anemometer and Vane

F420C or rugged model from any of several manufacturers, e.g., Climatronics Corporation; Climet; Meteorology Research, Inc.; R.M. Young Co.; Science Associates, Inc.; Teledyne Geotech; and Weather Measure, Inc.

B. Propeller on a Vane

Rugged model from any of several manufacturers, e.g., Beckman-Whitley; Belfort Instrument Co.; Bendix; and Weather Measure, Inc.

C. Vortex Anemometer Mounted on Vane (J-Tec Associates, Inc.)

D. Vortex Anemometer (Nonmoving Part) (J-Tec Associates, Inc.)

The cup and vane and the propeller on a vane each cost approximately \$600 per unit; however, in order to automate the readings from these sensors, the additional electronics would increase the cost to approximately \$1200. This figure is based on the cost of the electronic circuit cards for a Meteorology Research, Inc. sensor. These systems have seen extensive field use and their reliability and problems are well known.

The J-Tec Model VA300 vortex anemometer mounted on a vane has been used on the National Data Buoy System and costs approximately \$2000. A smaller sensor of the same type, Model VA320, is now being produced and costs approximately \$550. Displays for these sensors range from \$500 to \$600 depending upon the type selected (analog or digital).

The J-Tec Model VT-1003 vortex anemometer is a truly nonmoving-part system. Two of the sensors have been tested by the NWS Equipment Development Laboratory in the wind tunnel at the NWS Test and Evaluation Division (Lambert, 1976). At low air speeds, 2.6 m/s (5 knots) or less the direction error is 14^{o}. However, at speeds from 5.1 to 51.5 m/s (10 to 100 knots), the direction error is less than 5^{o}. The speed error from 2.6 to 30.9 m/s (5 to 60 knots) is within the manufacturer's specified limits (1 m/s or 5%) but, at 51.5 m/s (100 knots) the error exceeds 4.6 m/s (9 knots). All errors are rms values. If the manufacturer could deliver a system meeting the candidate system accuracy requirements, i.e, better accuracy below 5.6 m/s, it would have a number of desirable features:

(1) It would have no moving parts; therefore, it should require minimal maintenance.

(2) It would be designed for long periods of unattended operation.

(3) The output would lend itself to automation.

A present drawback of this system is the initial cost which is approximately \$3600 for quantity orders. Also, it is anticipated that both J-Tec sensor types could be affected by icing conditions like the cup and vane and propeller on a vane. None of the recommended sensor types should require additional electronic technician training or test equipment for maintenance. As previously stated, the J-Tec VA320 has approximately the same initial cost as either a cup and vane or a propeller on a vane but it has not been thoroughly field tested.

10. RECOMMENDATIONS

It is recommended that:

A. For the immediate future, either a cup and vane or a propeller on a vane wind system should be used for aviation purposes. The signal output should lend itself to automation. This wind system could be developed from existing commercial equipment or through modification to the F420C system.

B. A field test should be undertaken to test the J-Tec VA320 for functional precision; i.e., sensor-to-sensor variation, as well as comparability to both the F420C and a propeller-on-a vane type system.

C. The continued improvement of the vortex vector anemometer (no-moving parts) should be encouraged as a possible next-generation sensor.

D. Consideration should be given to testing other nonmoving-parts sensors such as the hot-film anemometer. While the cost of these systems is presently approximately $2500, advances in technology could reduce the cost. Knowledge gained during a long-term test under varying meteorological conditions would determine maintenance rates as well as comparability to present sensors.

TABLE I. SUMMARY OF OPERATIONAL SPECIFICATIONS FOR SELECTED ANEMOMETERS

MANUFACTURER	TYPE OF SENSOR	DISTANCE CONSTANT (63% Recovery) (m)	STARTING THRESHOLD (m/s)	ACCURACY	RANGE
	Cup & Vane				
Climatronics	Speed	2.4	0.22	1% or 0.07 m/s	0 to 63 m/s
Mark I	Direction	1.2	0.1 to 0.2		0 to 360°; 352° electrical
	Propeller & Vane				
R.M. Young	Speed	1.0	0.1 to 0.2	N/A	0 to 30 m/s
Model 35003	Direction	1.2	0.1 to 0.2	N/A	0 to 360°; 352° electrical
	Propeller & Vane				
Bendix	Speed	4.6	1.1	5 - 89 m/s: ± 0.45 m/s	0 to 89 m/s
Aero Vane 120	Direction	10.4	1.1	±2%	0 to 360°
EG&G; *	Sonic Anemometer				
Weather Measure;	Speed	6.9×10^{-1} at 45 m/s	0.02	3%	0 to 45 m/s
Intermetrics	Direction	N/A	N/A	±1%	0 to 360°
	Hot-Wire				
Thermo-Systems; Kyma	Speed	1×10^{-2}	0.01	±1%	0 to 25 m/s
	Direction	N/A	N/A	±6°	0 to 360°
Thermo-Systems	Ion Displacement				
Model 4400	Speed	Very Fast	0.01	0.3 m/s	0 to 45 m/s
J-Tech	Vortex Shedding				
Model VT-1003	Speed	6×10^{-3}	0.77	±2% full scale	0.77 to 52 m/s
J-Tech	Vortex Shedding				
Mounted on	Speed	6×10^{-3}	1.0	±2% full scale	1 to 60 m/s
Vane VA-320	Direction	10	N/A	±4° at 2 m/s	0 to 360°
Lockheed;	Laser Doppler				
Thermo-Systems	Speed	0.4×10^{-3}	N/A	± 0.5 m/s	0 to 1200 m/s
	Direction	N/A	N/A	±3°	0 to 1200 m/s

N/A Data Not Available

* When model numbers are not given parameters are indicative of the class.

TABLE II. COMPARISON OF COMMERCIALLY AVAILABLE ANEMOMETERS

SENSOR	ADVANTAGES	LIMITATIONS	COST	REMARKS
1. Cup Anemometer	With proper design, the response is essentially linear above instrument starting speed. Durable. Capable of operating to speeds of 103 m/sec (200 knots).	Has movable parts, bearings, etc., which require programmed maintenance. Affected by icing. Overspeeding due to dynamic effects is reported to be 5-10%.	Depending on manufacturer (model) and necessary output electronics, the cost for cup/vane systems range from approximately $500 to over $1000. (Recorders not included.)	Overestimate in speed can be calculated and corrected for. Instrument very suitable for synoptic observations. Overspeeding errors are correctable.
2. Propeller Mounted on Vane	Lightweight propellers exhibit greater linearity than cups. Rugged models for field use available.	Off axis response deviates from cosine law. Response limited by distance constant of vane, always larger than propellers. Same need for maintenance as cup anemometer.	Sensor costs approximately $600.	Most of these units are lightweight for turbulence measurements. More rugged models have long distance constant for vane, therefore are not usable in light and variable winds.
3. Two-Axis Fixed Propeller Anemometer	Simple in operation. Not limited by vane response.	Errors due to derivation from cosine response are significant. Some need for maintenance as cup anemometer. Not as rugged as cup anemometer. No commercial unit available which measures speed to the desired m/sec (125 knots).	Sensor and indicator cost approximately $700.	Corrections for cosine response can be made to improve accuracy.
4. Two-Axis Sonic Anemometer	No moving parts. Linear response and absolute calibration. Very suitable for light and moderate winds.	Velocity loss up to 10% when wind is along sensor axis (error highest for steady wind direction). Vibrates in strong winds. Precipitation causes spurious signals if transmitter or receiver crystals become covered with water. Operate to desired wind speeds (maximum operational speed is approximately 36 m/sec or 70 knots).	Sensor cost greater than $7000.	Extremely high sensor cost and need for extensive and costly peripheral equipment. Not seen as an operational field instrument.

	SENSOR	ADVANTAGES	LIMITATIONS	COST	REMARKS
5.	Hot Wire/ Hot Film Anemometers	Nonmovable part, linear sensor. Suitable for light and variable winds. Can be partially enclosed in a basket which protects them from hail and somewhat from heavy rain. Probes can withstand peak winds in excess of 150 m/sec (295 knots).	Accuracy is affected by high humidity. Probe surfaces must be washed regularly to remove deposited contaminants.	Hot film sensors range upwards from $2500.	Hot film anemometers are more durable and have greater long-term stability than hot wire anemometers. Hot wire anemometers are not suitable for general field use.
6.	Ion Displacement Anemometer	No moving parts. Small.	In the field it has been noted that high humidities affect and interrupt reading. Probe acts as an electrostatic precipitator and must be washed periodically. Will not measure winds above 51 m/sec (100 knots).	Sensor cost is approximately $2500.	Sensor output gives wind components therefore easily automated. Not seen as a continuously operational field instrument for NWS/FAA applications.
7.	Vortex Shedding Anemometer	A nonmovable part sensor which is rugged and requires virtually no maintenance.	Has a high "starting speed" with data not reliable below about 26 m/sec (5 knots). NWS wind tests sound wind speed tests up to 10% giving large errors at high wind speeds.	Sensor cost ranges from $1000 to $4500 depending on quantity and model.	Systems tested by the NWS Equipment Development Laboratory have not met manufacturers specifications.
8.	Vortex Shedding Mounted on Vane	The wind speed portion of the sensor has no movable parts. The sensor was designed to be operated unattended for periods up to one year.	Response limited by distance constant of vane. Sensor not reliable in light, variable wind speed situations.	Sensor costs range from $500 to $2000.	Designed for use on buoys for National Data Buoy Program.

SENSOR	ADVANTAGES	LIMITATIONS	COST	REMARKS
9. Laser Doppler Anemometer	No movable parts.	Only one component of wind is sensed. Optics would require maintenance on a regular basis.	Two sensors to measure the two wind components cost $28,000.	These are laboratory systems not suitable for continuous operational use. Extremely high sensor and peripheral equipment cost.
10. Laser Scintillation Anemometer	No movable parts. Measures mean flow (in one direction) over path lengths of at least 300 meters.	There is a need for an unobstructed portion at least 300 meters in each of two directions. The system will saturate (not operate properly) near the ground on hot days with a high level of surface heating. Precipitation will interfere with accuracy. Requires peripheral signal processing equipment.	Two sensors to measure the two wind components cost approximately $44,000.	Could not be used as a primary wind sensing instrument at an airport. Could be used as a secondary sensor to measure runway crosswinds, etc.

APPENDIX I

OPERATING SPECIFICATIONS OF COMMERCIALLY AVAILABLE ANEMOMETER TYPES

March 1977

This Appendix lists typical operating specifications for each sensor type. The specifications are for specific commercially available models. In addition, other manufacturers or distributors of similar equipment are listed where available. The information is from manufacturers' literature on indicated models.

1. CUP ANEMOMETER AND VANE

Manufacturers: R. M. Young Company
Climatronics Corporation
Climet
Meteorology Research Incorporated
Teledyne Geotech
Science Associates, Incorporated
Weather Measure, Incorporated

Sensor: Climatronics Wind Mark I

Wind Speed

Range: 0 to 63.3 m/s (0 to 109 knots)

Threshold: 0.22 m/s (0.43 knots)

Distance Constant: 2.4 meters (8 feet) with stainless steel cups

Accuracy: ± 1% or 0.067 m/s (0.13 knots) whichever is greater

Direction

Range: 0 to 360° mechanical, 352° electrical (7 to 9° open)

Threshold: 0.1 to 0.2 m/s (0.2 to 0.4 knots)

Distance Constant: 1.2 meters (3.9 feet)

Accuracy: Not available

2. PROPELLER MOUNTED ON VANE

A. Research Type

Manufacturers: R. M. Young Company
Meteorology Research Incorporated
Science Associates Incorporated

Sensor: R. M. Young Gill Propeller Vane, Model 35003

Wind Speed

Range: 0 to 30 m/s (0 to 58 knots)

Threshold: 0.1 to 0.2 m/s (0.4 to 0.4 knots)

Distance Constant: 1 meter (3.1 feet)

Accuracy:

Direction

Range: 0 to 360° mechanical 352° electrical (7 to 9° open)

Threshold: 0.1 to 0.2 m/s (0.2 to 0.4 knots)

Distance Constant: 1.2 meters (3.9 feet)

Accuracy: Not available

B. Rugged Type

Manufacturers: Bendix
Weather Measure Incorporated
Beckman-Whitley
Belfort Instrument Company

Sensor: Bendix Aerovane Model 120

Wind Speed

Range: 0 to 89 m/s (0 to 174 knots)

Threshold: 1.1 m/s (2.2 knots)

Distance Constant: 4.6 meters (15 feet)

Accuracy: 0 to 4.5 m/s (0 to 8.7 knots): ± 0.22 m/s (± 0.43 knots) 4.5 to 89 m/s (8.7 to 174 knots): ± 0.45 m/s (0.9 knots)

Direction

Range: 0 to 360°

Threshold: 1.1 m/s (2.2 knots) for full tracking

Distance Constant: 10.4 meters (34 feet)

Accuracy: $\pm 2^{\circ}$

3. FIXED PROPELLER (Two Axis)

Manufacturer: R. M. Young Company

Sensor: R. M. Young Gill UVW Anemometer Model 27004

Range: 0 to 22 m/s (0 to 43 knots) with sensitive propeller, 0 to 38 m/s (0 to 73 knots) with optional propeller for all angle flow

Threshold: 0.1 to 0.2 m/s (0.2 to 0.4 knots) with sensitive propeller, 0.2 to 0.3 m/s (0.4 to 0.6 knots) with optional propeller

Accuracy: Not listed; however, wind at 45° to propeller axis will have approximately 10% error in speed reading (from response graph).

4. SONIC ANEMOMETER

Manufacturers: EG&G Corporation
Weather Measure, Incorporated
Intermetrics

<u>Sensor</u> EG&G Model No. 199

<u>Wind Speed</u>

Range:	0 to 44.7 m/s (0 to 87 knots) 0 to 35.8 m/s (0 to 69 knots) on axis
Starting Speed:	0.0156 m/s (0.030 knots) (with 2 minute averaging)
Resolution:	0.0156 m/s (0.030 knots)
Averaging Time:	2 minutes
Distance Constant:	69 cm at 44.7 m/s (27 in. at 87 knots) 6.9 cm at 4.47 m/s (2.7 in. at 8.7 knots) 0.69 cm at 0.447 m/s (0.27 in. at 0.87 knots)
Gust Response:	16 milliseconds at 4.47 m/s (8.7 knots) Gust length = 4.4 km (2.7 miles)
Accuracy:	3% of reading, 3% of full scale

<u>Direction</u>

Range:	0 to 360°
Accuracy:	$\pm$ 1°
Resolution:	0.5°

5. HOTWIRE/HOT FILM ANEMOMETERS

Manufacturers:	Thermo-Systems Incorporated Kyma Corporation
Sensor:	Kyma Corporation Model 102
Range:	0 to 10 m/s (0 to 18 knots) or 0 to 25 m/s (0 to 49 knots) are standard. Other ranges can be supplied on special order.
Repeatability:	± 1% of true or 0.1 m/s (0.2 knots) whichever is greater
Threshold:	Less than 0.01 m/s (0.02 knots)
Distance Constant:	Each axis will respond to less than 1 cm (0.4 inch) of air flow

6. ION DISPLACEMENT ANEMOMETER

Manufacturer: Thermo-Systems Incorporated

Sensor: Thermo-Systems Model 4400

Velocity Range: 0 to 44.7 m/s (0 to 87 knots)

Threshold: 10^{-2} m/s (0.02 knots)

Frequency Response: 3 db point at 10 Hz

Dynamic Range: $5x10^3$

Accuracy: $\pm$0.3 m/s (0.6 knots)

7. VORTEX SHEDDING ANEMOMETER (No moving parts)

Manufacturer: J-Tech Associates, Incorporated

Sensor: J-Tech Model VT-1003
(Sensor output is vector components

Range: 0.77 to 51.5 m/s (1.5 to 100 knots)

Threshold: 0.77 m/s (1.5 knots)

Distance Constant: 6 mm (0.25 inch)

Component RMS Accuracy: ±2 % full scale

8. VORTEX SHEDDING MOUNTED ON VANE

Manufacturer: J-Tech Associates Incorporated

Sensor: J-Tech Model VA-320

<u>Wind Speed</u>

Range: 1 to 60 m/s (1.9 to 117 knots) at full accuracy to 80 m/s (155 knots) at reduced accuracy

Threshold: 1 m/s (1.9 knots)

Distance Constant: 6 mm (0.25 inch)

Accuracy: $\pm$ 2 % full scale

<u>Direction</u>

Range: 0 to 360^o

Distance Constant: 10 meters (33 feet)

Accuracy: $\pm$ 4^o at 2 m/s (39 knots)
$\pm$ above 4 m/s (7.8 knots)

Maximum Tolerable Wind: 100 m/s (194 knots)

9. LASER DOPPLER ANEMOMETER

Manufacturers: Lockheed Missiles & Space Engineering Co.
Thermo-Systems, Inc.

Sensor: Lockheed Laser System

Range: Can receive wind information out to a distance of 1210 meters (2000 feet).

Velocity Range: 0 to 1200 m/s (0 to 2330 knots)
System has been used to measure atmospheric winds to 67 m/s (130 knots)

<u>Accuracy</u>

Speed: Less than 0.5 m/s (1 knot)

Direction: $\pm 3^{o}$

10. LASER SCINTILLATION

Manufacturer: Campbell Scientific

Path Length: 300 meters to 10 kilometers
(1000 feet to 6.2 miles)

Full Scale Range: 5, 10, and 20 m/s
(9.7, 1.9, 39 knots)

Time Constant Selection: 1, 10, and 100 seconds time constants on velocity, correlation and log amplitude standard deviation measurements on both the meter and the recorder outputs.

Calibration Stability: Velocity ± 2 % of full scale

APPENDIX II REFERENCES

Atkinson, D., 1971: Forecasters' guide to tropical meteorology. Technical Report 240, Air Weather Service, USAF.

Badgley, F.I., 1970: Basic considerations for equipment design. Meteorological Observations and Instrumentation. Meteorological Monographs, Vol. 11, No. 33, American Meteorological Society, Boston, Mass., 185-194.

Beran, D.W., 1974: Remote Sensing Wind and Wind Shear System, Report No. FAA-RD-74-3, Federal Aviation Administration, Washington, D.C.

Bernstein, A.B., 1967: A note on the use of cup anemometers in wind profile experiments. Journal of Applied Meteorology, Vol. 6, 280-286.

Brown, R.M., 1976: Personal communication

Colton, R.F., 1974: Vortex anemometry - a new application of an old principal. Inst. Soc. Amer. reprint of paper presented at 20th Int. Instr. Symposium, 10 pp.

Corrsin, S., 1963: Turbulence: experimental methods. Handbuch der Physik, Vol. VIII/2, Springer Verlag, 525-590.

Crouser, H.H., 1967: Notes on wind measurement, ESSA Tech. Memo WBTM-EDL-2, U.S. Dept. of Commerce, 21 pp.

Dickson, C.R., 1976: Personal communication

Drinkrow, R., 1972: A solution to the paired Gill-anemometer response function. Journal of Applied Meteorology, Vol. 11, 76-80.

EG&G, 1975: Model 199 two axis anemometer system. TR75-025. Sonic anemometer instruction manual, 16 pp.

ESSA, 1969: Requirements statements for selected data acquisition equipment, ESSA Tech. Memo. WBTM DATAC 3, Dept. of Commerce.

Federal Meteorological Handbook No. 1, 1975: Surface observations. A10-3 to A10-13.

Fritschen, L.J., and R. Hinshaw, 1972: A reed switch anemometer. Journal of Applied Meteorology, Vol. 11, 742-744.

Hinze, J.O., 1959: Turbulence. McGraw-Hill, 586 pp.

Hinzpeter, M.F.E., 1975: A new versatile cup anemometer system for automated data acquisition. Automated Meteorological Systems. WMO No. 420, 148-157.

Huschke, R.E., 1959: Glossary of meteorology (ed), American Meteorological Society, Boston, Mass., 638 pp.

ICAO, 1967: Report on the fifth air navigation conference, Montreal, DOC, 8720, AN-CONF/5.

Ito, H., 1969: Time and space variation in meteorological elements in the aerodrome and its vicinity. Aeronautical Meteorology, WMO Tech. Note No. 95, 142-157.

Izumi, Y., and M.L. Barad, 1970: Wind speeds as measured by cup and sonic anemometers and influenced by tower structure. Journal of Applied Meteorology, Vol. 9, 851-856.

Kaimal, J.C., 1975: Sensors and techniques for direct measurement of turbulent fluxes and profiles in the atmospheric surface layer. Atmospheric Technology 7, 7-14.

Kaimal, J.C., 1976: Personal communication.

Kaimal, J.C., and J.A. Businger, 1963: A continuous wave sonic anemometer-thermometer. Journal of Applied Meteorology, Vol. 2, 156-167.

Kaimal, J.C., J.T. Newman, A. Bisberg, and K. Cole, 1971: An improved three-component sonic anemometer for investigation of atmospheric turbulence. Flow--Its Measurements and Control in Science and Industry, Vol. 1, I.S.A., 349-359.

Kjelaas, A.G., and G.R. Ochs, 1974: Study of divergence in the boundary layer using optical propagation techniques. Journal of Applied Meteorology, Vol. 13, 242-248.

Koren, O., 1973: Digital output wind system for airport use. Journal of Applied Meteorology, Vol. 12, 529-536.

Kovasznay, L.S.G., 1965: The hot-wire anemometer. Acta Sci. Hung., 50, 131-151.

Lambert, C., 1976: Personal communication.

Lawrence, R.S., G.R. Ochs, and S.F. Clifford, 1972: Use of scintillations to measure average wind across a light beam. Applied Optics, 11, 239-243.

Lea, D.A., and R.A. Helvey, 1971: A directional bias in wind roses due to mixed compass formats. Journal of Applied Meteorology, Vol. 10, 1037-1039.

Lockheed, 1974: Laser remote atmospheric monitoring system. LMSC-HREC SD D390259-1. Lockheed Missiles & Space Company, Inc. 38 pp.

MacCready, P.B., Jr., and H.R. Jex, 1964: Response characteristics and meteorological utilization of propeller and vane wind sensors. Journal of Applied Meteorology, Vol. 3, 182-193.

MacCready, P.B., Jr., 1966: Mean wind speed measurements in turbulence. Journal of Applied Meteorology, Vol. 5, 219-225.

Mazzarella, D.A. 1972: An inventory of specifications for wind measuring instruments. Second Symposium on Meteorological Observations and Instrumentation of the American Meteorological Society, pp 172-182

Merceret, F.J., 1976: Measuring atmospheric turbulence with airborne hot-film anemometers. Journal of Applied Meteorology, Vol. 15, 482-490.

Miyake, M., and F.I. Badgley, 1967: A constant temperature wind component meter and its performance characteristics. Journal of Applied Meteorology, Vol. 6, 186-194.

Pike, M., 1974: Atmospheric instrumentation--The impact of solid-state technology. Bulletin American Meteorological Society, Vol. 55, 1091-1094.

Ramachandran, S., 1969: A theoretical study of cup and vane anemometers. Quart. Journal Royal Meteorological Society, Vol. 95, 163-180.

Schwiesow, 1972: Wind profiles by laser scattering, (in) remote sensing wind and wind shear system. D.W. Beran, Report 1974, prepared for DOT FAA, 3.14-3.19.

SethuRaman, S., and R.M. Brown, 1976: A comparison of turbulence measurements made by a hot-film probe, a bivane, and a directional vane in the atmospheric surface layer. Journal of Applied Meteorology, Vol. 15, 138-144.

Sheih, C.M., 1972: Optimal choice of parameters for the measurement of small scale atmospheric turbulence with an airborne hot-wire anemometer. Journal of Applied Meteorology, Vol. 11, 81-84.

Sissenwine, N., P. Tattelman, D.D. Grantham, and I.L. Gringorten, 1973: Extreme wind speeds, gustiness and variations with height for MIL-STD210B. AFCRL-TR-73-0560, Air Force Surveys in Geophysics, No. 273, 72 pp.

Standards for Weather Bureau Field Programs, 1967: U.S. Department of Commerce, ESSA, 19-21.

Suomi, V.E., and J.A. Businger, 1959: Principal of the sonic anemometer thermometer. AFCRL-TR-58-235, Geophysics Research Papers No. 59, 673 pp.

Thermo-Systems, Inc., 1975: Hot-wire hot-film ion anemometer systems. TSI Cat/Form 6560373, 81-96.

Waletzko, J.A., 1975: A new ion displacement system to measure the two dimensional wind vector. Automated Meteorological Systems, WMO No. 420, 260-269.

Weather Bureau, 1970: Specification for wind measuring system (speed and direction). Specification No. F420C-SP001. Weather Bureau Engineering Division. 21 pp.

White, E., 1976: Personal communication.

Wieringa, J., 1967: Evaluation and design of wind vanes. Journal of Applied Meteorology, Vol. 6, 1114-1122.

Wieringa, J., and F.X.C.M. vanLindert, 1971: Application limits of double-fin and coupled wind vanes. Journal of Applied Meteorology, Vol. 10, 137-145.

World Meteorological Organization, 1971: Guide to Meteorological Instruments and Observing Practices, WMO No. 8. TP.3

World Meteorological Organization, 1975: Technical Conference on Automated Meteorological Systems, WMO No. 420, 380 pp.

Wyngaard, J.C., J.T. Bauman and R.A. Lynch, 1971: Cup anemometer dynamics AFCRL. Paper presented at the Symposium on Flow--Its Measurement and Control in Science & Industry, 9-14, May 1971, 27 pp.